Searching for dark energy off the beaten track

Sunny Vagnozzi

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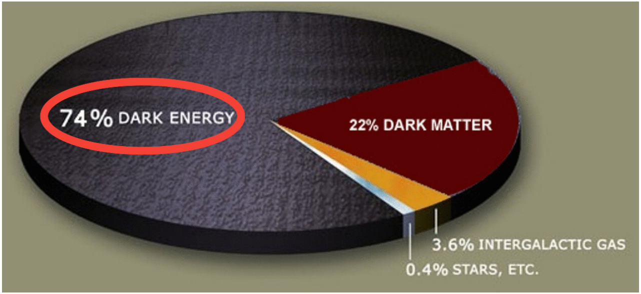
ETH Zürich, 5 July 2021

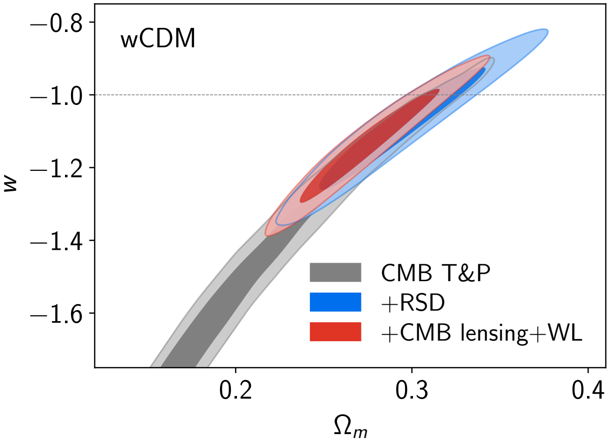
Dark Energy



- Part I: "*Direct Detection of Dark Energy*"
- Part II: (early and late) consistency tests of ΛCDM and what they might teach us about (early and late) dark energy
- Part III: new ways to search for dark energy and new light particles

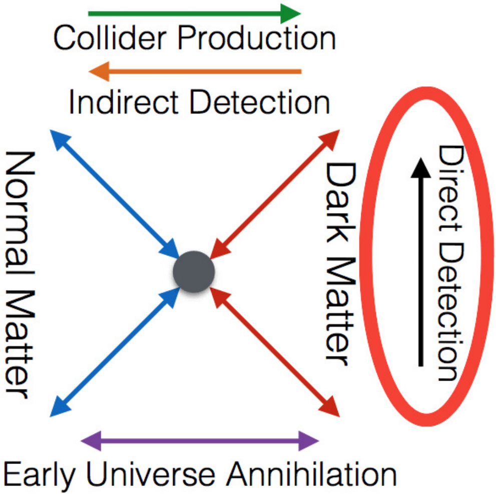
Understanding dark energy's properties

Lots of focus on understanding *gravitational* signatures of dark energy, and in particular constraining its equation of state w



eBOSS collaboration, PRD 103 (2021) 083533

Are gravitational signatures all there is?



What about dark energy?

Credits: (adapted from) Matt Buckley

Direct detection of dark energy

Can we detect dark energy in underground labs nominally devoted to the direct detection of dark matter?

Direct detection of dark energy: the XENON1T excess and future prospects

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[2] *Institute of Astronomy (IoA), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

[3] *Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy***

[4] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

[5] *Institute de Physique Théorique (IPhT), Université Paris-Saclay, CNRS, CEA, F-91191, Gif-sur-Yvette Cedex, France*

[6] *Department of Applied Mathematics and Theoretical Physics (DAMTP), Center for Mathematical Sciences, University of Cambridge, CB3 0WA, United Kingdom*

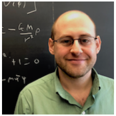
[7] *Department of Physics & Astronomy, University of Hawai'i, Watanabe Hall, 2505 Correa Road, Honolulu, HI, 96822, USA*

(Dated: April 1, 2021)

Luca Visinelli (INFN Frascati)

Phil Brax (IPhT, Saclay)

Anne Davis (Cambridge)



Jeremy Sakstein (Hawaii)

Can dark energy and visible matter talk to each other?

Quintessence and the Rest of the World: Suppressing Long-Range Interactions

Sean M. Carroll
Phys. Rev. Lett. **81**, 3067 – Published 12 October 1998

If DE due to a new particle, this typically will:

- be very light [$m \sim H_0 \sim \mathcal{O}(10^{-33})\,\mathrm{eV}$]
- have gravitational-strength coupling to matter (inevitable unless protected by a symmetry!)

Result/immediate obstacle: long-range fifth forces!

$$F_5 = -\frac{1}{M_5^2}\frac{m_1 m_2}{r^2}e^{-r/\lambda_5}\,, \quad M_5 \sim M_{\mathrm{Pl}}\,, \quad \lambda_5 \sim m^{-1} \sim H_0^{-1}$$

Screening

How to satisfy fifth-force tests?

- Tune the coupling to be extremely weak [$M \ll M_{\rm Pl}$]
- Tune the range to be extremely short [$\lambda \ll \mathcal{O}(\rm mm)$]
- Tune the dynamics so the force weakens based on its environment $\longrightarrow$ **screening**!

(At least) 3 ways to screen

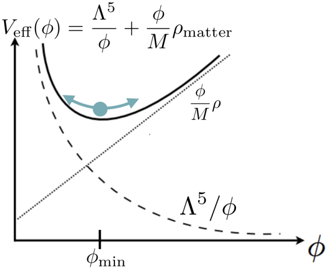
$$F_5 = -\frac{1}{M_5^2(\mathbf{x})} \frac{m_1 m_2}{r^{2-n(\mathbf{x})}} e^{-r/\lambda_5(\mathbf{x})}$$

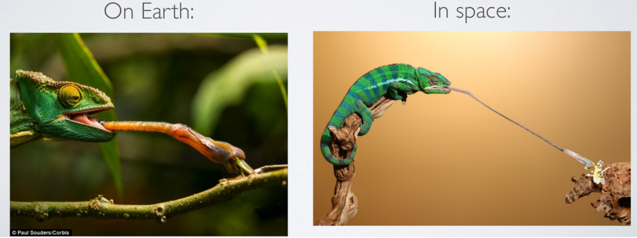
- $\lambda_5(\mathbf{x}) \rightarrow$ **chameleon** screening (short range in dense environments)
- $M_5(\mathbf{x}) \rightarrow$ symmetron screening (weak coupling in dense environments)
- $n(\mathbf{x}) \rightarrow$ Vainshtein (force drops faster than $1/r^2$ around objects)

Chameleon screening

Fifth force range $\lambda(\mathbf{x})$ becomes short in dense environments, scalar field minimizes effective potential determined by coupling to matter

$$
\begin{aligned}
V_{\text{eff}} &= V(\phi) + \phi\rho_m/M \\
m_{\text{eff}}^2 &= \frac{d^2 V_{\text{eff}}}{d\phi^2}\Big|_{\phi=\phi_{\min}} \propto \rho^n \,, \; n > 0 \\
\lambda &\sim 1/m_{\text{eff}} \propto \rho^{-n/2}
\end{aligned}
$$





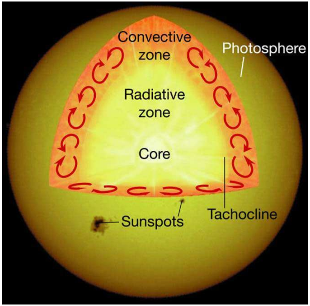
Credits: Ben Elder

Direct detection of dark energy

Production

$$\mathcal{L}_{\phi\gamma} \supset \underbrace{-\beta_\gamma \frac{\phi}{M_{\rm Pl}} F_{\mu\nu}F^{\mu\nu}}_{\text{(anomalous)}} + \underbrace{\frac{T_\gamma^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{M_\gamma^4}}_{\text{disformal}}$$

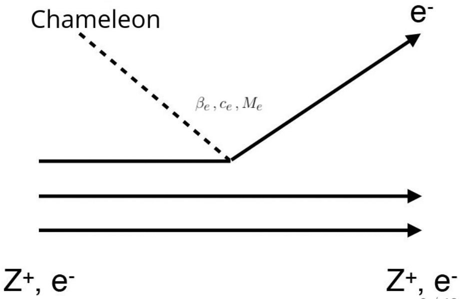
Production in strong magnetic fields of the tachocline



Detection

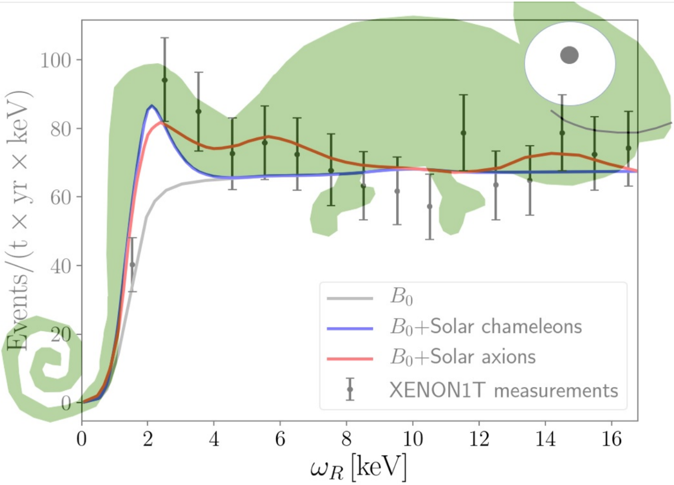
$$\mathcal{L}_{\phi i} \supset \underbrace{\beta_i \frac{\phi T_i}{M_{\rm Pl}}}_{\text{conformal}} - \underbrace{c_i \frac{\partial^\mu\phi\partial_\mu\phi}{M^4} T_i}_{\text{kinetic-conformal}} + \underbrace{\frac{T_i^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{M_i^4}}_{\text{disformal}}$$

Analogous to photoelectric and axioelectric effects



Direct detection of (chameleon-screened) dark energy

Best-fit DE-electron interaction cross-section $\sigma \sim \mathcal{O}(\mathrm{b}) \sim \mathcal{O}(10^{-25})\,\mathrm{cm}^2$



SV *et al.*, arXiv:2103.15834 Image editing credits: Cristina Ghirardini

Cosmological direct detection of dark energy

Wouldn't barn-scale DE scattering mess up all cosmological observables?

MNRAS **493,** 1139–1152 (2020)
Advance Access publication 2020 February 3
doi:10.1093/mnras/staa311

Do we have any hope of detecting scattering between dark energy and baryons through cosmology?

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[1] *Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands*
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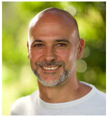
Surprisingly not!

Luca Visinelli (INFN Frascati)

Olga Mena (Valencia)



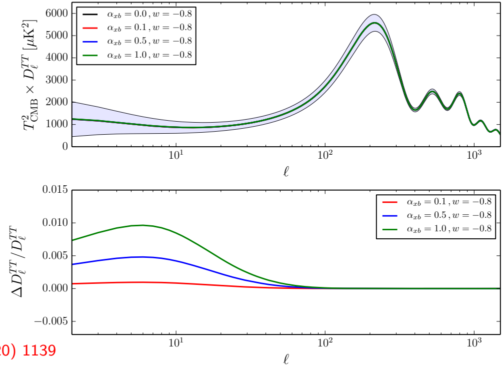
David Mota (Oslo)

Cosmological direct detection of dark energy

$$\dot{\theta}_b = -\mathcal{H}\theta_b + c_s^2 k^2 \delta_b + \frac{4\rho_\gamma}{3\rho_b} a n_e \sigma_T (\theta_\gamma - \theta_b) + (1+w_x)\frac{\rho_x}{\rho_b} a n_e \sigma_{xb}(\theta_x - \theta_b)$$

$$\dot{\theta}_x = -\mathcal{H}(1-3c_s^2)\theta_x + \frac{c_s^2 k^2}{1+w_x}\delta_x + a n_e \sigma_{xb}(\theta_b - \theta_x)$$

Impact on CMB ($\alpha = \sigma_{xb}/\sigma_T$)



SV *et al.*, MNRAS 493 (2020) 1139

Cosmological direct detection of dark energy

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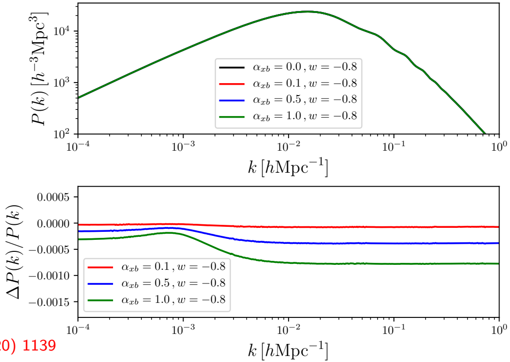
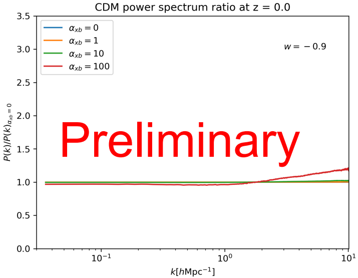
Impact on **linear** matter power spectrum ($\alpha = \sigma_{xb}/\sigma_T$)



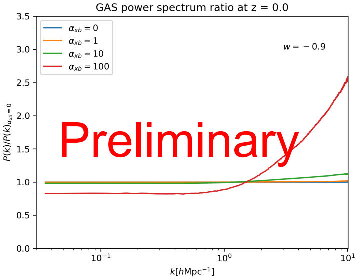
SV *et al.*, MNRAS 493 (2020) 1139

Cosmological direct detection of dark energy: N-body simulations

Impact on **non-linear** matter power spectrum



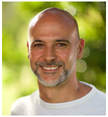
Ferlito, SV, Baldi, Mota, in preparation



Ferlito, SV, Baldi, Mota, in preparation

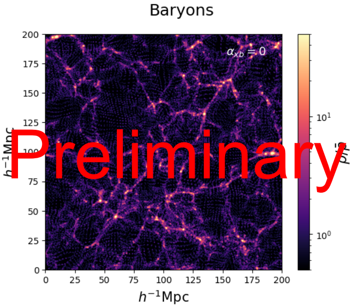
Fulvio Ferlito (Bologna)

Marco Baldi (Bologna)

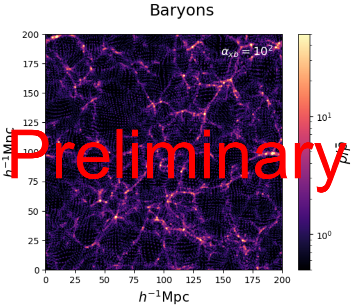


David Mota (Oslo)

Cosmological direct detection of dark energy: N-body simulations



Ferlito, SV, Baldi, Mota, in preparation



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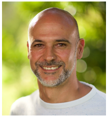
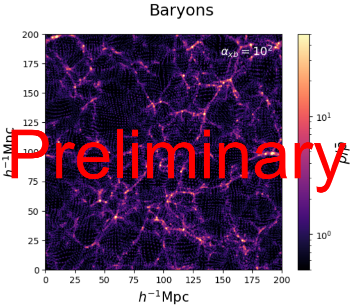
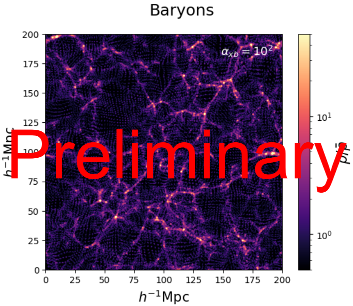


David Mota (Oslo)

Cosmological direct detection of dark energy: N-body simulations



Ferlito, SV, Baldi, Mota, in preparation



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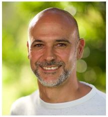


David Mota (Oslo)

Recap

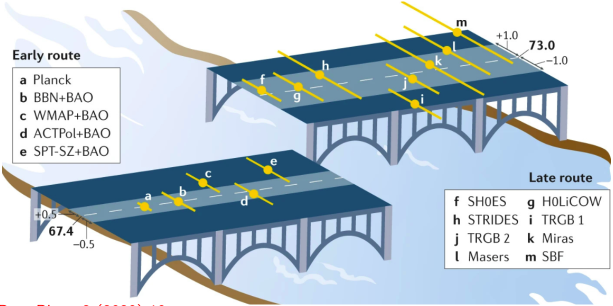
Direct detection of dark energy

- Lots of unharvested potential for direct detection of dark energy in dark matter direct detection experiments
- Room for large dark energy-baryons interactions in cosmology...
- ...possibly tightly constrained by (non-linear) LSS clustering!

Where else might we learn something about dark energy (at early and late times)?

Perhaps from the Hubble tension!

Viewing the Hubble tension ocean with different eyeglasses



Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

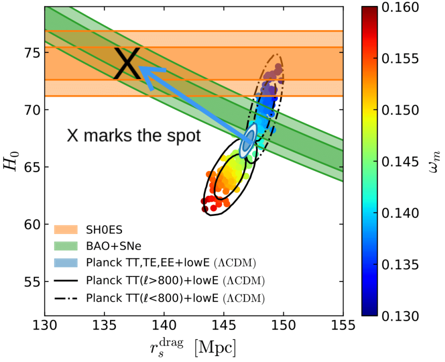
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Early times: early ISW effect	$\Longleftrightarrow$	*Consistency tests of ΛCDM*	$\Longleftrightarrow$	*Late times: ages of old objects*

The Hubble tension and new physics

Hubble tension *appears* to call for (substantial) early-time new physics...

Increasing $H(z)$ just prior to $z_\star$: "least unlikely" proposal?



Example: early dark energy (some debate as to how much it works)

Featured in Physics | Editors' Suggestion

Early Dark Energy can Resolve the Hubble Tension

Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski
Phys. Rev. Lett. **122**, 221301 – Published 4 June 2019

Editors' Suggestion

Early dark energy does not restore cosmological concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D **102**, 043507 – Published 5 August 2020

Need ≈ 12% (!!!) EDE around $z_{\rm eq} \Downarrow$

*Why is there no **clear** sign of new physics in CMB data alone?*

Credits: Knox & Millea, PRD 101 (2020) 043533

Early-time consistency tests of ΛCDM

Why is there no clear sign of early-time new physics in CMB data alone?

↓

Why does ΛCDM fit CMB data so well?

↓

(Early-time) Consistency tests of ΛCDM

The early ISW (eISW) effect

Around recombination: Universe not fully matter dominated $\implies$ residual decay of gravitational potentials $\implies$ eISW effect sources anisotropies

$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}} \right] j_\ell(k\Delta\eta)$$

$$\Theta_\ell^{\text{ISW}}(k) = \underbrace{\int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(A substantial amount of) New physics increasing $H(z)$ around $z_{\rm eq}/z_\star$ *should* leave an imprint on the eISW effect!

eISW consistency test

Consistency tests of ΛCDM from the early ISW effect: implications for early-time new physics and the Hubble tension

Sunny Vagnozzi[1,*]

[1] *Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

Introduce scaling amplitude/fudge factor $A_{\rm eISW}$ SV, arXiv:2105.10425

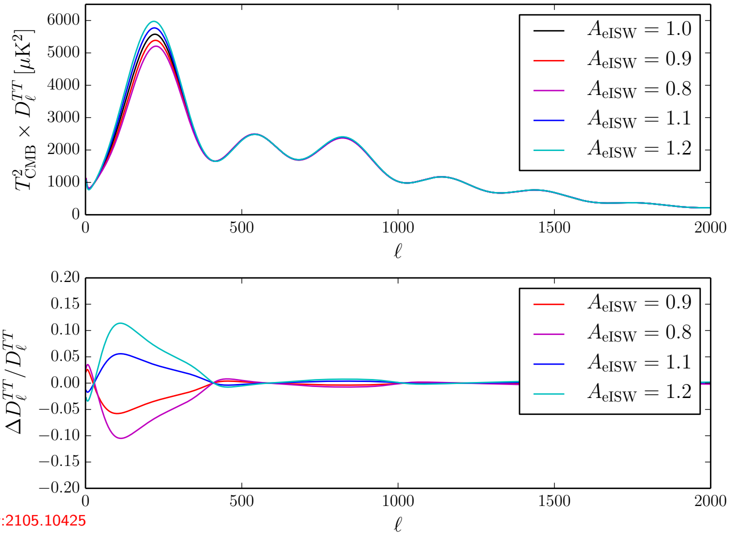
$$\Theta_\ell^{\rm eISW}(k) = A_{\rm eISW} \int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi} \right) j_\ell(k\Delta\eta)$$

Consistency check: within ΛCDM, is the data consistent with $A_{\rm eISW} = 1$?

Looks familiar? It should remind you of $A_{\rm lens}$ Calabrese *et al.*, PRD 77 (2008) 123531

$$C_\ell^{\phi\phi} \to A_{\rm lens} C_\ell^{\phi\phi}$$

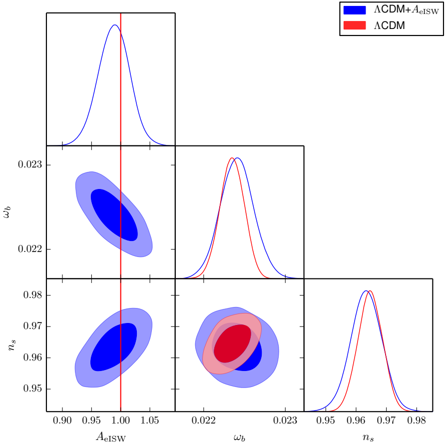
eISW consistency test



SV, arXiv:2105.10425

eISW consistency test

Is the data consistent with $A_{\text{eISW}} = 1$? (7-parameter ΛCDM+A_{eISW})



SV, arXiv:2105.10425

Yes!

Parameter	*Planck* ΛCDM	*Planck* ΛCDM+A_{eISW}
$100\omega_b$	2.235 ± 0.015	2.241 ± 0.020
ω_c	0.1202 ± 0.0013	0.1203 ± 0.0014
θ_s	1.0409 ± 0.0003	1.0409 ± 0.0003
τ	0.0544 ± 0.0078	0.0541 ± 0.0078
$\ln(10^{10}A_s)$	3.045 ± 0.016	3.046 ± 0.016
n_s	0.965 ± 0.004	0.963 ± 0.005
A_{eISW}	1.0	0.988 ± 0.027
H_0 [km/s/Mpc]	67.26 ± 0.57	67.28 ± 0.62
Ω_m	0.317 ± 0.008	0.317 ± 0.009

SV, arXiv:2105.10425

Other parameter constraints very stable, no more than $\approx 0.3\sigma$ shifts

Implications for early-time new physics: EDE case study

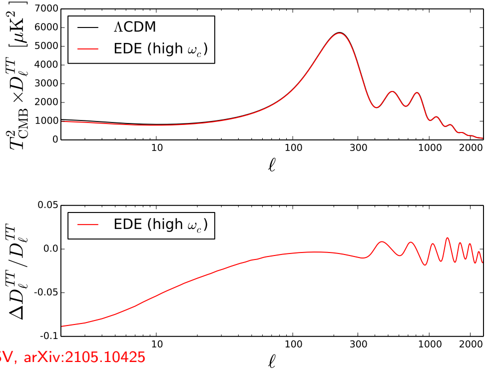
High H_0 EDE fit to CMB at the cost of increase in ω_c → worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, arXiv:2009.10740

Editors' Suggestion

Early dark energy does not restore cosmological concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D **102**, 043507 – Published 5 August 2020

Parameter	ΛCDM	EDE (high ω_c)	EDE (low ω_c)
$100\omega_b$	2.253	2.253	2.253
ω_c	0.1177	0.1322	0.1177
H_0 [km/s/Mpc]	68.21	72.19	72.19
τ	0.085	0.072	0.072
$\ln(10^{10}A_s)$	3.0983	3.0978	3.0978
n_s	0.9686	0.9889	0.9889
$f_{\rm EDE}$	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
θ_i	–	2.83	2.83
n	–	3	3

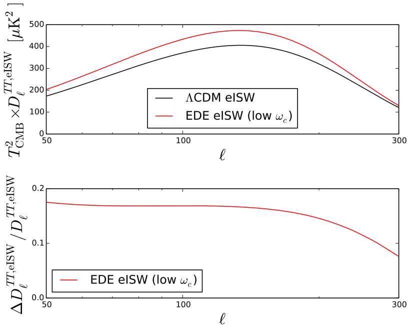


SV, arXiv:2105.10425

Implications for early-time new physics: EDE case study

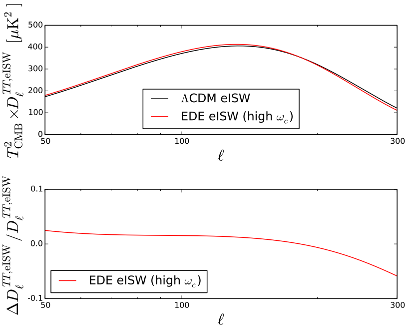
Let's extract only the eISW contribution to temperature anisotropies...

Low ω_c



Almost 20% eISW excess!

High ω_c

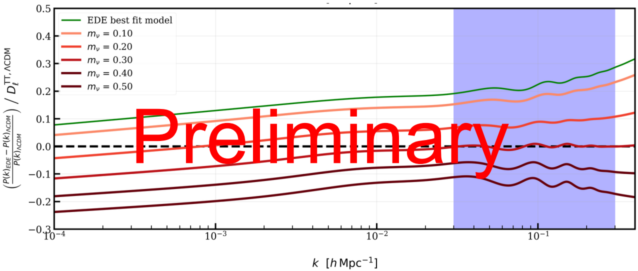


No more than $\lesssim$ 3-5% eISW excess

Generic to models increasing pre-recombination $H(z)$, not just EDE

Early dark energy problems

Example: neutrino mass (nominally need $M_\nu \sim 0.3\,\mathrm{eV}$ to rescue EDE!)



Reeves, SV, Efstathiou, Sherwin, in preparation. Plot credits: Alex Reeves

Other possible ingredients: decaying DM, DM-dark radiation interactions (work in progress)

Alex Reeves (Cambridge → ETH)

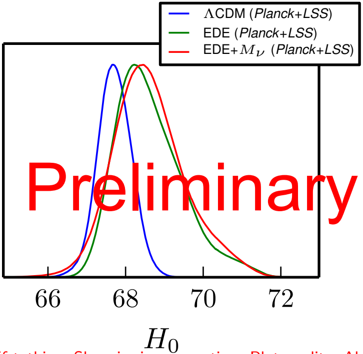
George Efstathiou (Cambridge)

Blake Sherwin (Cambridge)

Early dark energy problems

Massive neutrinos actually turn out not to work:

- Increase in S_8 (actually worsens S_8 discrepancy)
- M_ν negatively correlated with H_0 for CMB
- Need $M_\nu \sim 0.3\,\mathrm{eV}$, very hard to accommodate in LSS data



Reeves, SV, Efstathiou, Sherwin, in preparation. Plot credits: Alex Reeves

Alex Reeves (Cambridge → ETH)

George Efstathiou (Cambridge)

Blake Sherwin (Cambridge)

Aside: S_8 discrepancy – something to get excited about?

MNRAS 505, 5427–5437 (2021)
Advance Access publication 2021 June 5
https://doi.org/10.1093/mnras/stab1613

Arbitrating the S_8 discrepancy with growth rate measurements from redshift-space distortions

Rafael C. Nunes[1]★ and Sunny Vagnozzi[2]†
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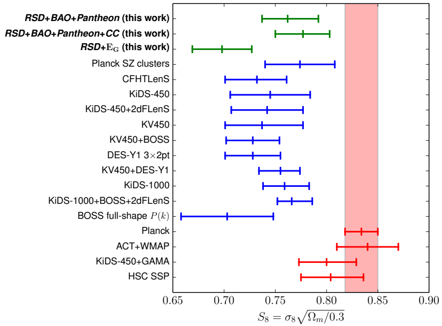
[2]Kavli Institute for Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

- Always important to look at tensions/discrepancies with a different set of eyeglasses
- From the growth rate ($f\sigma_8$) point of view, S_8 discrepancy perfectly compatible with a statistical fluctuation!

Rafael Nunes (INPE, Brazil)



Nunes & SV, MNRAS 505 (2021) 5427

Is ΛCDM really all there is at late times?

↓

(Try to) Test ΛCDM making no assumptions about early-time physics

↓

Learn something about H_0 in the process?

Old astrophysical objects at high redshift

Historically (1960s-1998) high-z OAO provided the first hints for the existence of dark energy ($\Omega \neq 1$, $\Omega_\Lambda > 0$)

A 3.5-Gyr-old galaxy at redshift 1.55

James Dunlop, John Peacock, Hyron Spinrad, Arjun Dey, Raul Jimenez, Daniel Stern & Rogier Windhorst

Nature **381**, 581–584 (1996) | Cite this article

Conflict over the age of the Universe

M. Bolte & C. J. Hogan

Nature **376**, 399–402 (1995) | Cite this article

The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker & Paul J. Steinhardt

Nature **377**, 600–602 (1995) | Cite this article

What can OAO do for cosmology in the 2020s?

Cosmology with old astrophysical objects

Can the ages of the oldest inhabitants of the Universe teach us something about the Universe's contents (including DE) and the Hubble tension?

Implications for the Hubble tension from the ages of the oldest astrophysical objects

Sunny Vagnozzi,[1,*] Fabio Pacucci,[2,3,†] and Abraham Loeb[2,3,‡]

[1] *Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2] *Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA*
[3] *Black Hole Initiative, Harvard University, Cambridge, MA 02138, USA*

Fabio Pacucci (Harvard)

Avi Loeb (Harvard)

Yes, while probing a region where ΛCDM may still break ($1 \ll z \lesssim 10$)!

Cosmology with old astrophysical objects

$$t_U(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \propto \frac{1}{H_0}$$

Pros and cons:

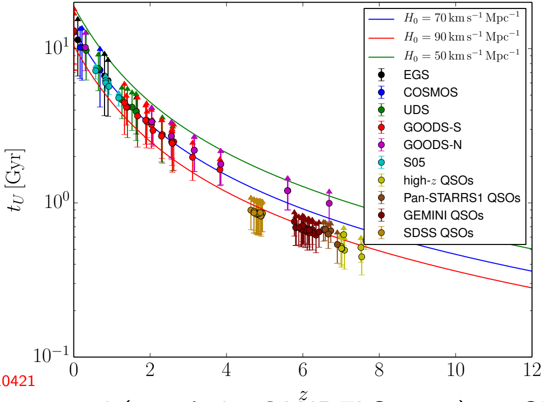
- OAO cannot be older than the Universe $\rightarrow$ **upper limit on $\mathbf{H_0}$**
- $t_U(z)$ integral insensitive to early-time cosmology
- $\implies$ **late-time consistency test for ΛCDM independent of the early-time expansion**!
- Ages of astrophysical objects at $z > 0$ hard to estimate robustly ⚠

Usefulness in relation to the Hubble tension:

- Contradiction between OAO upper limit on H_0 and local H_0 measurements could indicate the need for non-standard late-time ($z \lesssim 10$) physics, or non-standard local physics
- Conclusions completely independent of pre-recombination physics

OAO age-redshift diagram

Age-redshift diagram up to $z \sim 8$



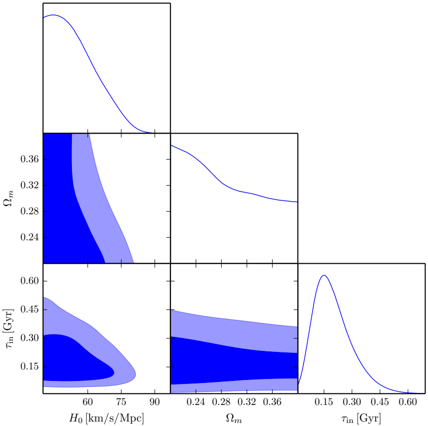
SV *et al.*, arXiv:2105.10421

Galaxy ages estimated (mostly by CANDELS team) via SED fitting, QSOs ages via growth model Pacucci *et al.*, ApJ Lett. 850 (2017) L42

Results

Assume ΛCDM at late times, constrain H_0, Ω_m, and incubation time $\tau_{\rm in}$

Prior for $\tau_{\rm in}$ following Jiménez *et al.*, JCAP 1903 (2019) 043; Valcin *et al.*, JCAP 2012 (2020) 022



- $H_0 < 73.2$ (95% C.L.)
- $\approx 2\sigma$ tension with Cepheid-calibrated SNeIa H_0 measurement
- Tighter (but less robust) results using non-flat prior on Ω_m
- (in principle can also constrain w, Ω_K,...)

SV *et al.*, arXiv:2105.10421

Implications for the Hubble tension

CAVEAT – if the OAO ages are reliable, possible explanations include:

- #1: ΛCDM is not the end of the story at $z \lesssim 10$
- #2: Nothing wrong with ΛCDM at $z \lesssim 10$, need local new physics...

  Examples: screened 5th forces (Desmond *et al.*, PRD 100 (2019) 043537; Desmond & Sakstein, PRD 102 (2020) 023007), breakdown of FLRW (Krishnan *et al.*, arXiv:2105.09790; arXiv:2106.02532),++
- #3: Just a boring 2σ fluke or systematics?

If #1, maybe the answer to the Hubble tension is a combination of (mostly) pre-plus-post-recombination new physics?
If #2, maybe the Hubble tension is not cosmological, but non-local vs local discrepancy? See hints for this in Lin, Chen & Mack, arXiv:2102.05701

Several other hints that pre-recombination new physics alone not enough to solve Hubble tension Krishnan *et al.*, PRD 102 (2020) 103525; Jedamzik *et al.*, Commun. Phys. 4 (2021) 123; Lin *et al.*, arXiv:2102.05701; Dainotti *et al.*, ApJ 912 (2021) 150

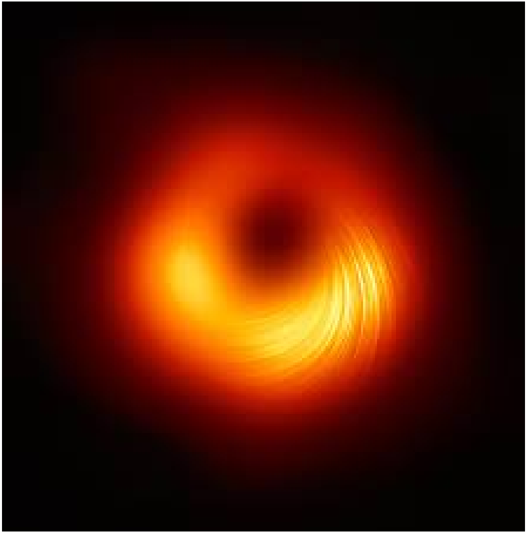
Recap

Consistency tests of ΛCDM

- Early times: no signs of new physics in early ISW effect $\rightarrow A_{\mathrm{eISW}} \approx 1$ sets important challenge for early-time new physics (EDE case study)
- Late times: slight discrepancy between ages of oldest astrophysical objects (upper limit on H_0) and local H_0 measurements
- Early-time new physics *alone* not enough for the Hubble tension?

Other ways to learn about dark energy or more generically new light particles?

Fundamental physics from black hole shadows



Credits: Event Horizon Telescope collaboration

Testing the rotational nature of the supermassive object M87* from the circularity and size of its first image

Cosimo Bambi, Katherine Freese, Sunny Vagnozzi, and Luca Visinelli
Phys. Rev. D **100**, 044057 – Published 29 August 2019

Hunting for extra dimensions in the shadow of M87*

Sunny Vagnozzi and Luca Visinelli
Phys. Rev. D **100**, 024020 – Published 12 July 2019

Magnetically charged black holes from non-linear electrodynamics and the Event Horizon Telescope

Alireza Allahyari[1], Mohsen Khodadi[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 4 February 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, February 2020
Citation Alireza Allahyari *et al* JCAP02(2020)003

Concerns regarding the use of black hole shadows as standard rulers

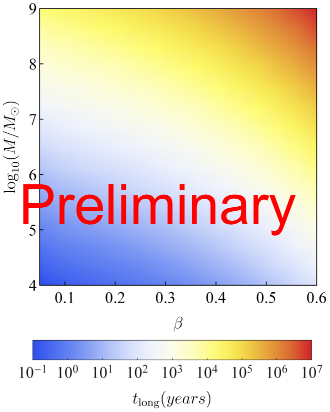
Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]
Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001

Black holes with scalar hair in light of the Event Horizon Telescope

Mohsen Khodadi[1], Alireza Allahyari[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020
Citation Mohsen Khodadi *et al* JCAP09(2020)026

New light particles and (time-evolving) black hole shadows

Superradiance: light boson cloud growth with $GmM_{\rm BH} \sim r_{\rm BH}/\lambda_c \sim \mathcal{O}(1)$ at the expense of BH mass/angular momentum



Roy, SV, Visinelli, in preparation

Superradiance evolution of black hole shadows revisited

Rittick Roy,[1,*] Sunny Vagnozzi,[2,†] and Luca Visinelli[3,4,5,‡]

[1] *Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, China*
[2] *Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy*
[4] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
[5] *Tsung-Dao Lee Institute (TDLI) and School of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, China*

- Consistent modelling in the presence of gas accretion and GW emission
- Change in shadow size $\sim \mathcal{O}(1)\mu\text{as}$ potentially observable on human timescales $[\mathcal{O}(10)\,\text{yr}]$

Rittick Roy

(Fudan)

Luca Visinelli

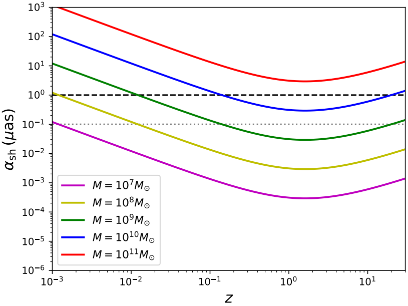
(INFN Frascati)

Black hole shadows as standard rulers?

Concerns regarding the use of black hole shadows as standard rulers

Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]

Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001



SV *et al.*, CQG 37 (2020) 087001

$$\alpha_{\rm sh}(z) \simeq \frac{3\sqrt{3}M}{D_A(z)}$$

Problems:

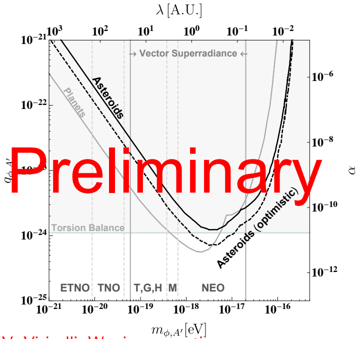
- Reliably determining M
- Model-dependence (beyond GR)
- Understand high-z SMBHs well?

Cosimo Bambi (Fudan)

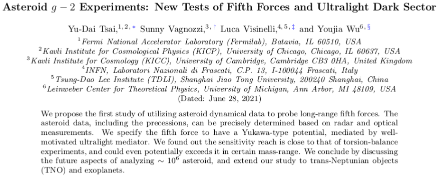
Luca Visinelli (INFN Frascati)

Precession of celestial objects and new light particles

Precession from new light (gauged) mediators-induced fifth force



Tsai, SV, Visinelli, Wu, in preparation



Asteroid $g-2$ Experiments: New Tests of Fifth Forces and Ultralight Dark Sector

Yu-Dai Tsai,[1,2,*] Sunny Vagnozzi,[3,†] Luca Visinelli,[4,5,‡] and Youjia Wu[6,§]

[1] *Fermi National Accelerator Laboratory (Fermilab), Batavia, IL 60510, USA*
[2] *Kavli Institute for Cosmological Physics (KICP), University of Chicago, Chicago, IL 60637, USA*
[3] *Kavli Institute for Cosmology (KICC), University of Cambridge, Cambridge CB3 0HA, United Kingdom*
[4] *INFN, Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy*
[5] *Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China*
[6] *Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109, USA*

(Dated: June 28, 2021)

We propose the first study of utilizing asteroid dynamical data to probe long-range fifth forces. The asteroid data, including the precessions, can be precisely determined based on radar and optical measurements. We specify the fifth force to have a Yukawa-type potential, mediated by well-motivated ultralight mediator. We found out the sensitivity reach is close to that of torsion-balance experiments, and could even potentially exceeds it in certain mass-range. We conclude by discussing the future aspects of analyzing $\sim 10^6$ asteroid, and extend our study to trans-Neptunian objects (TNO) and exoplanets.

- Celestial objects: asteroids, exoplanets, TNOs
- Competitive with torsion balance tests

Yu-Dai Tsai (Fermilab/KICP, Chicago)

Luca Visinelli (INFN Frascati)

Youjia Wu (Michigan)

Conclusions

- Direct detection of dark energy: huge unharvested potential and complementarity beyond laboratory searches and cosmological probes
- (Early- and late-time) Consistency tests of ΛCDM: early-time new physics *alone* most likely not enough to solve the Hubble tension
- Promising to probe new light particles (and dark energy?) with black hole shadows and precessions of celestial objects

Much to be learned about dark energy beyond "standard" cosmological searches for its gravitational interactions